

AD-A281 042



(1)

OFFICE OF NAVAL RESEARCH

CONTRACT N00014-94-1-0101

R&T Code 31321075

Technical Report No. 16

"LIVING" RADICAL POLYMERIZATION. I POSSIBILITIES AND LIMITATIONS.

by

Dorota Greszta, Daniela Mardare, Krzysztof Matyjaszewski

Published

in the

Macromolecules, 27, 638 (1994)

**Carnegie Mellon University
Department of Chemistry
4400 Fifth Avenue
Pittsburgh, PA 15213**

DTIC QUALITY INSPECTED 2

S F DTIC E' ECTE D
JUN 3 0 1994

June 30, 1994

Reproduction in whole or in part is permitted for any purpose of the United States Government

**This document has been approved for public release and sale;
its distribution is unlimited.**

94-20031



94 6 29 091

This report contains neither recommendations nor conclusions of the Defense Intelligence Agency or the Department of Defense. It has been reviewed by the Office of Management and Budget and approved for public release under the Freedom of Information Act. Distribution, use of data, and the costs associated with doing so, will be determined by the data owner. If you have comments regarding this burden estimate or any other aspect of this form, please address them to the Director, Defense Intelligence Agency Services Directorate for Information Operations and Requirements, Suite 1224, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED	
	June 30, 1994	Technical Report # 16	
4. TITLE AND SUBTITLE "Living" Radical Polymerization. I. Possibilities and Limitations			S. FUNDING NUMBERS N00014-94-1-0101
6. AUTHOR(S) D. Greszta, D. Mardare, K. Matyjaszewski			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Carnegie Mellon University Department of Chemistry 4400 Fifth Avenue Pittsburgh, PA 15213			8. PERFORMING ORGANIZATION REPORT NUMBER N00014-94-1-0101
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Department of the Navy Office of Naval Research 800 North Quincy Street Arlington, VA 22217-5000			10. SPONSORING/MONITORING AGENCY REPORT NUMBER Technical Report # 16
11. SUPPLEMENTARY NOTES Macromolecules, <u>27</u> , 638 (1994)			
12a. DISTRIBUTION/AVAILABILITY STATEMENT		12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Possibility of the synthesis of well-defined polymers by radical polymerization is discussed. Kinetic analysis demonstrates that the preparation of polymers with controlled macromolecular structure in a "living" radical process requires low stationary concentration of growing radicals which are in a dynamic equilibrium with dormant species. Three approaches are described. First, when growing radicals react reversibly with scavenging radicals to form covalent species, second when growing radicals react reversibly with covalent species to produce persistent radicals and the third in which growing radicals participate in the degenerative transfer reaction which regenerates the same type of radicals. Some of the reported "living" radical systems are critically evaluated.			
14. SUBJECT TERMS		15. NUMBER OF PAGES	
		16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Classified	18. SECURITY CLASSIFICATION OF THIS PAGE Classified	19. SECURITY CLASSIFICATION OF ABSTRACT Classified	20. LIMITATION OF ABSTRACT UL

1.5.1 DM

"Living" Radical Polymerization.

I. Possibilities and Limitations.

Dorota Greszta, Daniela Mardare, and Krzysztof Matyjaszewski*

Department of Chemistry

Carnegie Mellon University

4400 Fifth Avenue

Pittsburgh, PA 15213

Abstract:

Possibility of the synthesis of well-defined polymers by radical polymerization is discussed. Kinetic analysis demonstrates that the preparation of polymers with controlled macromolecular structure in a "living" radical process requires low stationary concentration of growing radicals which are in a dynamic equilibrium with dormant species. Three approaches are described. First, when growing radicals react reversibly with scavenging radicals to form covalent species, second when growing radicals react reversibly with covalent species to produce persistent radicals and the third in which growing radicals participate in the degenerative transfer reaction which regenerates the same type of radicals. Some of the reported "living" radical systems are critically evaluated.

Dist	Avail or Special
A-1	

Introduction

Synthetic polymer chemistry has been recently focused on the control of macromolecular and supramolecular structures. This includes the preparation of polymers with novel architectures such as cyclic, threaded, and ladder structures as well as various types of block and star polymers and copolymers which may microphase separate into domains of various geometries. Synthesis of well defined polymers requires high chemoselectivity, regioselectivity and stereoselectivity. High chemoselectivity is observed in living polymerizations when chain growth is not disturbed by any chain breaking reactions. Chemoselectivity is probably the most important parameter because it affects macromolecular dimensions, defines the end groups of polymer chains and is a prerequisite for the formation of block copolymers. High chemoselectivity is observed in living polymerizations when chain growth is not disturbed by any chain breaking reactions. If initiation is fast, then the degree of polymerization is defined by the ratio of the reacted monomer to the introduced initiator:

$$DP_n = \Delta[M] / [I]_0 \quad (1)$$

Living polymerization is most often observed in chain reactions which proceed with polar growing species such as ions or organometallic compounds. In these systems, active species react with monomer and sometimes may terminate in reactions with impurities or intentionally added terminators. Chain ends do not react one with another due to electrostatic repulsions. On the other hand, free radicals, which are the growing species in radical polymerization, very easily react with one another via coupling and/or

disproportionation. Thus, it is inherently difficult to imagine a living radical polymerization.

Recent Developments in Living Polymerization with the Special Emphasis on Carbocationic Polymerization

Living polymerization was initially reported for the anionic polymerization of alkenes and dienes in which the growing carbanions survive for a period of time greatly exceeding that necessary for complete monomer conversion¹. Quite good living systems were also described for the anionic ring opening polymerization of epoxides and the cationic ring-opening polymerization of various heterocyclics (ethers, sulfides, amines, iminoethers, etc.) in which olate and onium ions are quite stable^{2,3}. Living polymerization was recently extended to systems which are more difficult to control such as polymerization of acrylates^{4,5,6}, metathesis polymerization of cycloolefins⁷ and others. Various living systems are discussed in a recent review⁸.

Recently well defined polymers have been prepared by the cationic polymerization of alkenes^{9,10,11}. This process was historically difficult to control and even thought to be impossible to convert into a living system. It is instructive to look closer at this system because some methods used to improve the "livingness" of the cationic polymerization may be used successfully in radical systems¹². Progress in the cationic polymerization of alkenes can be ascribed to the better understanding of the reaction mechanism and to the correct choice of initiator, additives and reaction temperature. Transfer is the major chain breaking reaction in this system due to the facile elimination of β -H atoms (partially positively charged) from the growing carbocations. The reactions carried out in the absence of basic components (counterions, solvent, additives) provide better defined systems due to the

suppression of the unimolecular (spontaneous) transfer. However, transfer to monomer still exists and can be reduced only at sufficiently low temperatures. The proportion of chains marked by transfer increases with conversion and with the polymerization degree (DP). In the case of "spontaneous" transfer (for example in cationic polymerization, transfer to solvent, counterion, etc.), the ratio of the observed number average DP to the theoretical DP ($DP_{(T)}$, no transfer) decreases with conversion p and with the product of the concentration of initiator times the ratio of the rate constants of transfer to propagation:

$$DP/DP_{(T)} = 1/\{1 + \ln[1/(1-p)] \cdot (k_{tr}/k_p)/[I]_0\} \quad (2)$$

As shown in Figure 1 the ratio $DP/DP_{(T)}$ decreases monotonously with conversion. The drop is the most pronounced for the highest value of the parameter $[k_{tr}/k_p]/[I]_0$. The ratio of the rate constants is given by "chemistry". i.e. mechanism, counterion, monomer, solvent, temperature, etc. However, the concentration of initiator can be easily controlled and "poor" systems with e.g. experimental DP four times lower than theoretically expected can be converted to well defined systems by increasing the concentration of initiator by 10 or 100 fold. This necessitates the synthesis of shorter chains. For sufficiently short chains, transfer may not be noticed. Thus, polymerization degrees corresponding to those described by eq. 1 may be obtained if initiation is fast in comparison with propagation and DP low enough not to be marked by transfer. This requires relatively high concentrations of the initiator ($[I]_0 \geq 10^{-2} \text{ mol}\cdot\text{L}^{-1}$). Carbocations react very rapidly with alkenes ($k_p \approx 10^5 \text{ mol}^{-1}\cdot\text{L}\cdot\text{s}^{-1}$ at $\approx 20^\circ\text{C}$). Thus, if all growing chains will be in the form of carbocations, polymerization may be finished in a fraction of second and may

be difficult to control or even explosive. In order to reduce polymerization rates, a dynamic equilibrium between reactive carbocations and dormant species was used. Reversible ionization of covalent species and reversible formation of onium ions provides well defined systems with the number of chains (M_n) defined by the total concentration of growing and dormant species ($[I]_0 \approx 10^{-2} \text{ mol}\cdot\text{L}^{-1}$) but with the rates proportional to the concentration of carbocations present at very low amounts ($[C^+] \approx 10^{-7} \text{ mol}\cdot\text{L}^{-1}$)).

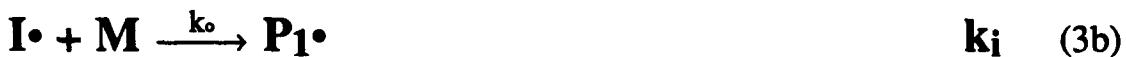
Fundamentals of Radical Polymerization

Radical polymerization includes four elementary reactions:

-slow initiation by the homolytic cleavage of a molecule with low thermal stability (peroxide, diazo, or organometallic compounds); $k_d < 10^{-5} \text{ s}^{-1}$,



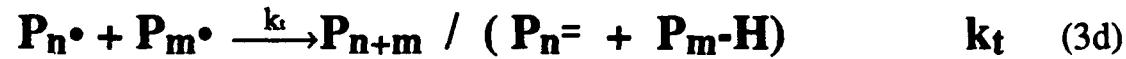
-relatively fast reaction of primary radicals with monomer to generate the first growing species; because $k_d < k_o[M]$, the decomposition is the rate determining step:



-fast propagation with moderate regioselectivity and low stereoselectivity; $k_p \approx 10^3 \text{ mol}^{-1}\cdot\text{L}\cdot\text{s}^{-1}$,



-very fast termination between growing radicals; $k_t = 10^7 \text{ mol}^{-1}\text{L}\cdot\text{s}^{-1}$;



transfer reactions are less important, unless transfer agents are added.

A typical synthesis of high molecular weight polymers requires slow initiator decomposition producing a low momentary concentration of growing radicals which terminate in a bimolecular process. Because termination is bimolecular, higher radical concentrations would produce shorter chains. The proportion of chains marked by any side reaction (transfer in cationic process and termination in a radical process) increases with chain length. Therefore, well defined polymers by radical polymerization may be formed only if chains are relatively short and concentration of free radicals is low enough. These two requirements are in an apparent contradiction but can be accommodated via reversible deactivation of growing free radicals in a way similar to the aforementioned deactivation of growing carbocations. Another possibility to fulfill the requirements for a low stationary concentration of radicals and short chains is to use conventional initiating systems with very efficient transfer reagents which will regenerate the same (or similar) growing radicals, see next sections.

Kinetic Requirements for a Living Radical Polymerization

Living polymerization should provide well defined polymers with a negligible amount of chain breaking. The criteria of livingness have not been well defined but it has been stressed that the chain breaking should not be observable (<5%) at the time of complete conversion of a monomer (>99%) for a synthetically convenient reaction (>10 minutes). The time criterion is more important for ionic reactions which are usually much faster than radical reactions and will not be discussed here.

In Figure 1, the top two curves correspond to 5% deactivation of chains at 99% conversion and 10% deactivation at 70% conversion. The behavior of

radical systems is different from cationic. The most important chain breaking reaction in the latter is transfer (cf. Figure 1) which has little or no effect on rates and leads to a higher number of chains (lower molecular weights) than expected. In radical reactions, termination is the most important chain breaking process. With fast initiation, the total number of chains is constant (assuming termination by disproportionation) and molecular weights close to theoretical ones are expected. At the same time, termination reduces the number of active chains, resulting in the decrease in polymerization rates, which will be accompanied by an increase in polydispersities.

From the point of view of the synthesis of well defined polymers, block copolymers and end-functional polymers, any chain breaking reaction is disallowed. However, termination and transfer will lead to different deviations from the behavior of ideal systems (either lower rates or lower DP).

As discussed in the previous section, the synthesis of well defined polymers by living polymerization should occur in systems with a low momentary (stationary) concentration of growing radicals which should be reversibly deactivated to provide a relatively large number of macromolecules. To control molecular weights in a sufficient way, the initiation rate should be at least comparable to that of propagation. Thus, let's assume that the initiator of the structure P-R is the adduct of the model of growing radical P[•] and a scavenging radical R[•]. R[•] can only react with P[•] but not with monomer (M) and cannot initiate polymerization. The covalent adduct homolytically cleaves to P[•] and R[•] with the rate constant of activation, k_{act}, and reforms with the rate constant of deactivation, k_{deact}:



Assuming a steady state for the concentration of dormant chains:

$$-d[P-R] = k_{act}[P-R] \cdot k_{deact}[P\cdot][R\cdot] \approx 0 \quad (5)$$

$$[P\cdot]_{st} = k_{act} [P-R] / (k_{deact}[R\cdot]) \quad (6)$$

or, if $[P\cdot]=[R\cdot]$:

$$[P\cdot]_{st} = (k_{act} [P-R] / k_{deact})^{1/2} \quad (7)$$

Growing radicals will also participate in propagation (no concentration change) and in undesirable irreversible termination:

$$-d[P\cdot]/dt = k_t [P\cdot]^2 + k_r[P\cdot][R\cdot] - k_i[P-R] \quad (8)$$

The deactivation is not considered as a chain breaking because it is reversible. Irreversible termination produces entirely inactive chains by either coupling or disproportionation of growing radicals $P\cdot$. The stationary concentration of growing radicals is constant because, although some chains are terminated, the radicals are easily reformed from the large pool of dormant species (dormant species are at least million times more populous than growing radicals). Because we are concerned mostly with well-defined systems, only a small fraction of the growing chains (dormant and active) can be deactivated ($\approx 5\%$). This 5% of the chains will terminate within time (τ_t) :

$$0.05 [P-R]_0 = k_t [P\cdot]_{st}^2 \tau_t \quad (9)$$

This approximate equation will be valid only for relatively low proportion of terminated chains ($\leq 20\%$), after which the decrease of $[P-R]$ has to be accounted for.

Monomer is consumed with a rate proportional to the concentration of the monomer, growing radicals and to the rate constant of propagation k_p :

$$-\frac{d[M]}{dt} = k_p [P^\bullet] [M] \quad (10)$$

99% of monomer will be consumed at time τ_p , which for a good living system should be comparable or shorter than the time when 5% of chains terminate (τ_t):

$$\ln ([M]_0 / 0.01[M]_0) = k_p [P^\bullet]_{st} \tau_p \quad (11)$$

Therefore:

$$[P^\bullet]_{st} / [P-R]_0 < k_p / 100 k_t \quad (12)$$

If less rigorous living criteria are set (10 % of chains terminated within a time of 70% conversion), then:

$$[P^\bullet]_{st} / [P-R]_0 \approx k_p / 10 k_t \quad (13)$$

Thus, depending on the quality of the system, either equation (12) or (13) may be used.

Below is given the analysis of the polymerization of styrene for which kinetic parameters are well known. At 60 °C, $k_p \approx 10^2 \text{ mol}^{-1} \cdot \text{L} \cdot \text{s}^{-1}$ and $k_t \approx 10^7 \text{ mol}^{-1} \cdot \text{L} \cdot \text{s}^{-1}$. The stationary concentration of growing radicals is estimated as

$$[\text{P}\cdot]_{\text{st}} = [\text{P}-\text{R}]_0 \cdot k_p / k_t \cdot 100 \approx 10^{-9} \text{ mol} \cdot \text{L}^{-1} \quad (14)$$

when targeting better defined system (eq. 12), using $[\text{M}]_0 = 1 \text{ mol} \cdot \text{L}^{-1}$, and synthesizing a polymer with $\text{DP} = 100$ ($[\text{P}-\text{R}]_0 = [\text{M}]_0 / \text{DP} = 10^{-2} \text{ mol} \cdot \text{L}^{-1}$).

At such a low $[\text{P}\cdot]_{\text{st}}$, a 99% conversion will be reached after $\approx 4 \cdot 10^7 \text{ s}$ which is more than one year!

The dynamics of the homolytic cleavage (activation) and recombination (deactivation) is very important. The upper limit for the rate constant of the recombination reaction between a growing radical and a scavenging radical is set by diffusion ($k_{\text{deact}} \approx 10^9 \text{ mol}^{-1} \cdot \text{L} \cdot \text{s}^{-1}$). If no excess scavenger is present ($[\text{P}\cdot] \approx [\text{R}\cdot]$), then:

$$k_{\text{act}} = k_{\text{deact}} [\text{P}\cdot] [\text{R}\cdot] / [\text{P}-\text{R}] \approx k_{\text{deact}} [\text{P}\cdot]^2 / [\text{P}-\text{R}] \approx 10^{-7} \text{ s}^{-1} \quad (15)$$

Therefore, the activation is extremely slow and 90% of the dormant species will be consumed only after more than half a year! If the structure of the initiator would be very similar to that of the dormant growing species, the rates of the homolytic cleavage of the initiator and of the dormant growing species will be also very similar.

The role of a scavenger of the growing radicals may be also played by a neutral species. In that case, a stable adduct with an odd number of electrons (a persistent radical) will be reversibly formed:



The kinetic requirements for this case (II) are identical to those for the previously discussed case (I).

There is another possibility for the synthesis of well defined polymers. Radicals present at certain low concentrations, or formed continuously during slow initiation may react in the transfer process with some agents which will reform radicals of the same or similar structure as growing radicals. This transfer is thermodynamically neutral and may be considered as the degenerative exchange process. If the exchange (transfer) is fast and the ratio of terminated chains to the total amount of chains low, then a well-defined system (III) may still be formed:



In this case, the main requirement for a living system is that a growing radical (P_n^\bullet) reacts rapidly and selectively with a transfer agent (P_1-R) to exchange the R and form a dormant species P_n-R and a new radical P_1^\bullet capable of chain growth. The latter after addition of ($m-1$) monomer units (P_m^\bullet) will react again with a transfer agent (P_n-R) to form P_m-R and P_n^\bullet . If this exchange is fast, polymers with a narrow MWD can be prepared. Degrees of polymerization will be defined by the ratio $\Delta[M]/[P-R] = DP$ and the reaction rate by a low concentration of stationary radicals P^\bullet . This concentration has to be kept low enough to reduce the possibility of bimolecular termination.

Thus, small differences exist between the previously discussed systems I and II and the case III. In case I, the homolytic cleavage of dormant species (P_n-R) to a scavenger and a growing radical ($R\cdot$ and $P_n\cdot$) occurs. In the case II and III the growing radical reacts with a non-radical (species with even number of electrons); in the case II, the concentration of these species is approximately equal to that of the growing species and the resulting persistent radical is at a very high concentration. In the case III, the concentration of the growing species is much lower than that of the transfer agent and unstable radicals ($[P_n-R-P_m]\cdot$) might be formed only as an intermediate product.

Polydispersities in the systems discussed will depend on the relative rate of initiation and termination as well as on the rate of exchange between active and dormant species¹³.

The first estimates of the possibilities for a living radical polymerization for styrene, are not very optimistic. A good living system requires extremely lengthy reactions and precludes practical applications. However, there are possibilities to improve the living radical polymerization systems.

Possible Improvements for Living Radical Systems

The slow overall polymerization rate, limited by a low stationary concentration of growing radicals, makes the living radical polymerization impractically slow. Very low values of the initiation prevents preparation of well defined systems because of the incomplete initiation. This will lead to higher than expected molecular weights and broader molecular weight distribution due to slow initiation and slow exchange between dormant and growing species.

There are three general ways to make living polymerization faster. The first method is based on lowering the criteria for the well defined system.

Thus, using eq. 13 (10 % deactivation at 70% conversion) will reduce polymerization time 10 fold in comparison with eq. 12 (5% deactivation at 99% conversion). In the previously discussed case of styrene, polymerization time can be reduced from one year to one month. Potentially, the reaction time can be further reduced, however, at expense of the loss of the macromolecular control.

The second approach is based on the increase of $[P-R]_0$. Increasing $[P-R]_0$ will, however, reduce DP unless it is accompanied by the corresponding increase of $[M]_0$. Thus, working in bulk ($[M]_0 \approx 10 \text{ mol}\cdot\text{L}^{-1}$) will enable 10 times increase of $[P-R]_0$ and ten times faster polymerization than in more dilute system ($[M]_0 \approx 1 \text{ mol}\cdot\text{L}^{-1}$) without decreasing DP. This may lead to a reduction in the polymerization time from one month to three days. Of course, the polymerization must be slower if higher molecular weight polymers are desired.

The third approach is based on the increase of the k_p/k_t ratio. Once again, there are a few methods to do that. The first is to increase the polymerization temperature. Since the activation energy of propagation is always higher than that of termination, the k_p/k_t ratio will increase with temperature. There is, however, a limit to use this approach since at temperatures above 90°C a spontaneous thermal initiation occurs for most vinyl monomers. The second possibility for the enhancement of the k_p/k_t ratio is an increase of pressure. Propagation has a negative volume of activation, termination a positive one (mostly due to the viscosity effect) and propagation will be favored at higher pressures. The third possibility is also related to viscosity. Polymerization in bulk will provide more viscous systems with higher k_p/k_t ratio. Additionally, similar effects may be accomplished by the correct choice of solvents and reaction media. The Tromsdorff effect is not

expected in living radical systems because radicals will be predominantly consumed in the reaction with a low molecular weight scavenger. Finally, the k_p/k_t ratio changes strongly with the monomer structure. For example, k_p/k_t ratio increases in the order: ethylene<styrene<methyl methacrylate<vinyl acetate<methyl acrylate ($0.0005 < 0.03 < 0.2 < 1 < 2.1$) $\times 10^{-4}$ at 60°C ¹⁴.

Thus, methyl acrylate allows a 70 times higher stationery concentration of growing radicals than styrene under otherwise similar conditions. This may lead to a reduction in the polymerization time to hours, which is comparable to conventional radical polymerization.

One comment should be added on the potential participation of solvent cage effects. It is possible that the homolytic cleavage of dormant chains will be accompanied by a very fast recombination of the growing radical with a scavenger within a solvent cage rather than with one arriving from the outside. This may lead to recombination faster than diffusion controlled rates and also to an enhanced k_p/k_t ratio due to the easier penetration of the solvent cage by a small monomer molecule rather than by the growing radical. This could allow synthesis of well defined systems at higher stationary concentrations of radicals and shorter reaction times than in the "classic" systems without contribution of the solvent cage. In fact, the solvent cage may be interpreted as a selective insertion of monomer into P - R bond and only some trapping experiments, solvent effects or copolymerization studies may confirm the true radical nature of propagation. The limiting case for these systems may be a radical-coordinative polymerization in which a nearly concerted process can take place.

The dynamics of the exchange should eventually be enhanced and activation accelerated. This can be accomplished by the more facile homolytic cleavage (higher k_{act}) and by the simultaneous shift of the equilibrium to the

same low stationary concentration of the growing radicals with the scavenger used in excess.

These scavengers should be selective in the reaction with growing radicals but should not react with an alkene and should not initiate polymerization. They might dimerize but some radicals are sufficiently stable and do not dimerize (TEMPO, galvinoxyl, etc.).

The second approach, based on the formation of persistent radicals, best realized with organometallic compounds. However, some of them may have a high affinity towards hydrogen and may lead to the undesired and uncontrolled transfer.

The third approach, based on transfer reagents, requires very selective compounds which will exclusively provide thermodynamically neutral degenerative transfer with rates comparable or faster than that of propagation. Because transfer agents are present at concentrations much lower than that of the monomer, ($[P-R]_0 \approx [M]_0/DP$), rate constants of transfer must be much faster than the propagation rate constants.

Brief Review of Reported Living Radical Systems

This section does not pretend to be comprehensive, but to be rather selective in discussing a few systems which may be interesting from the point of view of the aforementioned approach to living systems.

All of the systems are based (sometimes by chance) on a lower stationary concentration of growing radicals and suppression of the termination process by various means. This may include physical means (precipitation, emulsions, inclusion complexes, template polymerization, stiff chains, viscous media) or chemical means such as a decrease of the

concentration of growing radicals by the reversible termination with scavengers¹⁵.

Unfortunately, some of the systems used are far from being ideal: initiation is slow, scavengers react with monomers and reversibility is not observed except under photochemical conditions, and some side reactions lead to decomposition products. Criteria for living systems are often not obeyed and most reactions were limited only to low conversions (<10%). Molecular weights do not increase linearly with conversion and polydispersities are broad. Nevertheless, in some systems block copolymers have been prepared but as will be discussed later, probably not via chain extension reactions.

The discussion will be based on three types of living systems described above.

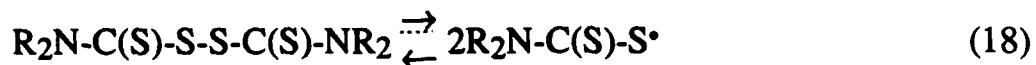
System I based on reversible recombination of growing radicals with scavenging radicals.

This system is very often postulated as the main operating system in the thermal polymerization with alkoxyamines or with alkyl dithiocarbamates. However, both of these systems conform better to case III (degenerative transfer).

Probably the best example of the case I is the photochemical polymerization with dithiocarbamate derivatives, usually tetraalkylthiuram disulfide. In early 1980s, Otsu reported a living radical polymerization of alkenes with this compound and described its action as inifer or iniferter which means that it acted as initiator, transfer agent and terminator¹⁶. The systems with thiuram disulfide as iniferter are usually characterized by the initial rapid growth and then a monotonous increase in molecular weight with conversion. In some cases, molecular weights do not increase linearly with

conversion, however. The polymerization obeys a first order kinetics in monomer as often observed for stationary state conditions. Molecular weight distribution remains fairly constant but usually not below $M_w/M_n \approx 2$.

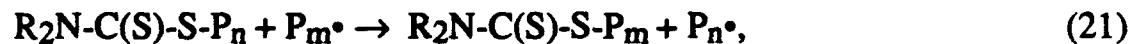
Systems initiated with dithiocarbamate derivatives behave differently when initiated thermally and photochemically. Thiuram disulfide is a poor photochemical initiator and starts to act efficiently only at temperatures above 90 °C¹⁷:



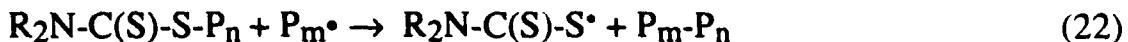
This may be ascribed to low reactivity of the primary radicals $R_2N-C(S)-S^\bullet$. These radicals slowly initiate polymerization and rapidly scavenge growing radicals to form dithiocarbamate end groups which are quite thermally stable but which cleave homolytically in the presence of light:



Growing radicals may also react with dithiocarbamates end groups in two different ways: by transfer process as suggested by Otsu¹⁶:



and additionally by irreversibly forming head-to-head end groups and producing thiocarbamate radicals of low reactivity. The latter reaction reported by Sigwalt is very important in thermal polymerization of acrylates^{18,19}:



Thermal polymerization of acrylates in the presence of benzyl dithiocarbamate is slower (!) than spontaneous thermal polymerization¹⁹. This means that the degradative transfer is the main operating reaction. On the other hand, photochemical cleavage of the NC(S)S--C bond may provide reversible systems conforming to system I¹⁷.

In addition, side reactions such as the evolution of CS₂ was reported and leads to additional complications²⁰:

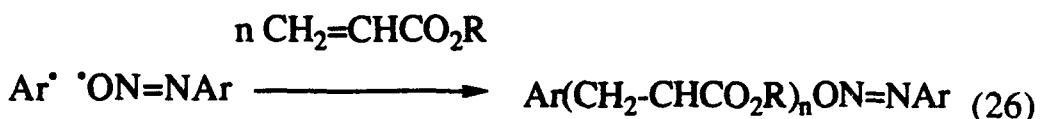


Another class of thermal initiators which provide systems of type I is based on tetraarylethanes^{21,22} and phenylazotriphenylmethane²³:



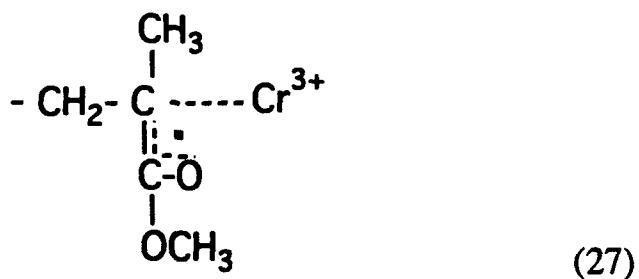
The bulky Ar₂RC• or Ar₃C• species play a role of scavenging radicals. A good living system should require fast initiation which is usually not fulfilled in these systems. Most studies with these compounds provided poly(methyl methacrylate) with relatively poor control of molecular weights and polydispersities.

Recently, a new series of initiators, generated from hyponitrite, arenediazoate or cyanate anions by reaction with electron-acceptors such as arenediazonium ions or activated alkyl halides, have been shown to provide long-lived oxygen-centered radicals²⁴. The "living" nature of these polymerizations was partially demonstrated by a quasi-linear increase in DP_n with conversion or by synthesis of block-copolymers of the type poly(methyl methacrylate)-poly(butyl acrylate). However, broad polydispersities (2.0 - 3.0) and low conversions were obtained:



System II based on the reaction of growing radicals to form reversible persistent radicals.

There are several papers describing radical polymerization of acrylic monomers (methyl methacrylate, acrylonitrile, methyl acrylate, acrylamide) by initiation with "aged" chromium acetate (Cr²⁺) and benzoyl peroxide (BPO), suggesting that a "living" polymerization occurs at temperatures below 30°C²⁵. An important factor is the presence of strong electron donors such as DMF or HMPA. The mechanism of this radical polymerization is discussed in terms of a transition metal complex (Cr³⁺) stabilized by the growing radicals:



These systems have very low activity towards styrene, vinyl acetate and vinyl chloride.

Organometallic derivatives of Ni(0), oxidized in one-electron transfer processes in the presence of certain organic halides (R-X) are useful initiators (iniferters) in unconventional free-radical polymerization of styrene and methyl methacrylate, allowing the synthesis of block-copolymers of the type polystyrene-poly(methyl methacrylate)²⁶.

A main problem with derivatives of transition metals is their high affinity towards hydrogen which results in β -hydrogen elimination from growing radicals and formation of the unsaturated chain ends. This is the case of Co⁺² used successfully as chain-transfer reagents in free-radical polymerization of acrylic monomers^{27,28}.

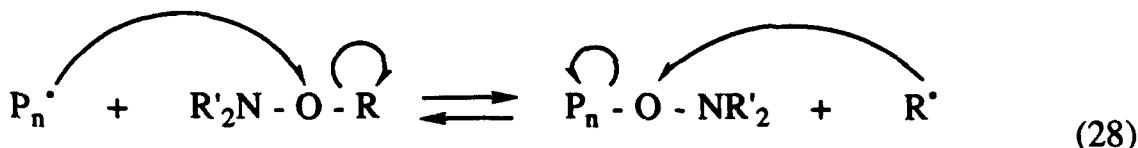
Nevertheless, if the affinity of transition metals towards hydrogen could be reduced by a proper choice of ligands, systems based on organometallic compounds are among the most promising.

System III based on the degenerative transfer.

The concept of the thermodynamically neutral degenerative transfer has not been intentionally used yet. In fact, it is very similar to the inifer system but the species are not initiators per se and require the use of true radical initiators. These initiators can be added in controlled amounts like in the polymerization with alkoxyamines as transfer agents²⁹. The role of the initiator may be played by impurities or even by the product of decomposition of transfer agents (alkyl dithiocarbamates)¹⁶.

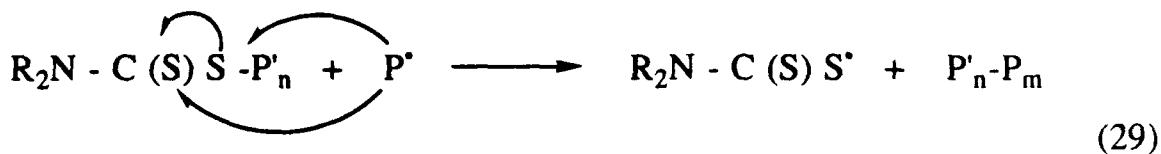
Some of the best controlled polymers obtained by radical polymerization are prepared with preformed alkoxyamines or those prepared

in situ²⁹. Alkoxyamines alone are inefficient initiators, unless at very high temperatures, but they might react easily with radicals. Thus, radical polymerization initiated by classic initiators (AIBN, peroxides, etc.) in the presence of alkoxy amines provides polymers with molecular weights determined by a number of alkoxyamines and rates determined by the stationary concentration of growing free radicals. This is possible when a macromolecular radical ($P_n\cdot$) attacks alkoxyamine selectively at the oxygen atom forming a macromolecular alkoxyamine and releases a radical $R\cdot$ capable of initiation of new chains:



This is probably the main reaction responsible for the formation of well defined polymers in these systems³⁰. Indeed, successful polymerization with TEMPO and alkoxyamines require an excess of radical initiator. Alkoxyamine may be prepared in advance or generated in situ by the reaction between TEMPO and initiator in the presence of monomer.

As discussed previously, dithiocarbamates are poor thermal initiators because they initiate slowly, do not reversibly form radicals and participate in the degradative rather than in the degenerative transfer. According to the results of Sigwalt^{18,19}, alkyl dithiocarbamate reduces the rate of spontaneous thermal polymerization of butyl acrylate but allows some control of molecular weights. This has been explained by the degradative transfer (top arrows):



This type of transfer may also lead to the formation of block copolymers with the macromolecular dithiocarbamate. Thus, block copolymers may not be formed via typical chain extension process but rather via coupling of a growing polyB with a polyA-terminated with dithiocarbamate moiety³¹. The synthesis of the well defined polymers will require very high chemoselectivity of the degenerative transfer (bottom arrow) and a very small contribution of the degradative transfer.

The prerequisite for a good degenerative transfer agent is high chemoselectivity (no β -H abstraction) and transfer rapid in comparison with propagation. In that case all chains will grow simultaneously and polymers with narrow molecular weight distribution may be prepared.

In the papers which follow this introductory article, the new approach based on the reversible deactivation of growing radicals with organoaluminum compounds will be presented. This system provides the first well defined poly(vinyl acetates) with $M_w/M_n < 1.2$ and molecular weights up to $M_n \approx 30,000$ ³² as well as block copolymers between poly(vinyl acetate) and various alkenes³³.

ACKNOWLEDGMENTS

Acknowledgment is made to the National Science Foundation, via the support within Presidential Young Investigator Award to K.M., as well as to Du Pont, Eastman Kodak, PPG Industries, and Xerox Corporation for the matching funds.

References:

1. Szwarc, M. *Carbanions, Living Polymers, and Electron Transfer Processes*, Wiley, New York 1968
2. Flory, P.J. *Principles of Polymer Chemistry*, Cornell University Press, Ithaca 1953.
3. Penczek, S., Kubisa, P., Matyjaszewski, K. *Adv. Pol. Sci.*, 1985, 68/69, 1
4. Sogah, D. Y., Hertler, W. R., Webster, O. W., Cohen, G. M. *Macromolecules*, 1988, 20, 1473
5. Teyssie, P. *Makromol. Chem., Macromol. Symp.*, 1991, 32, 61
6. Kunkel, D., Mueller, A. H. E., Janata, M., Lochman, L. *Makromol. Chem., Macromol. Symp.*, 1992, 60, 315
7. Grubbs, R. H., Gilliom, L. R. *J. Am. Chem. Soc.*, 1986, 108, 733
8. Webster, O. W. *Science*, 1991, 251, 887
9. Faust, R.; Kennedy, J. P. *Polym. Bull.*, 1986, 15, 317
10. Sawamoto, M. *Progr. Polym. Sci.*, 1991, 16, 111
11. Matyjaszewski, K. *Makromol. Chem. Macromol. Symp.*, 1992, 54/55, 51.
12. Matyjaszewski, K. *J. Polym. Sci., Chem.*, 1993, 31, 995
13. Matyjaszewski, K.; Lin, C. H. *Makromol. Chem. Macromol. Symp.*, 1991, 47, 221.
14. Eastmond, G. C., in "*Comprehensive Chemical Kinetics*", Vol.14A, C. H. Bamford, C. F. H. Tipper Eds., American Elsevier, New York, 1976.
15. Harwood, H. J., in "*Encyclopedia of Polymer Science and Technology*", Supplement Volume, Wiley, New York, 1989, p.429.
16. Otsu, T., Yoshida, M., *Makromol..Chem.Rapid Commun.*, 1982, 3, 127, 133.

17. Van Kerckhoven, C., Van der Broeck, H., Smets, G., Huybrechts, J., *Makromol. Chem.* **1991**, *192*, 101
18. Lambrinos, P., Tardi, M., Polton, A., Sigwalt, P., *Eur. Polym. J.* **1990**, *26*, 1125.
19. Dika Manga, J., *PhD. Thesis*, **1992**, *Univeristy of Paris*
20. Turner Richard, S., Blevins, R.W., *Macromolecules* **1990**, *23*, 1856.
21. Bledzki, A.; Braun , D. *Makromol. Chem. Rapid Commun.* **1982**, *3*, 127
22. Bledzki, A.; Braun, D.; Titzchkau, K. *Makromol. Chem.* **1983**, *184*, 745
23. Otsu, T., Yoshida, M., *Polym. Bull.*, **1986**, *16*, 277
24. Druliner, J.D. *Macromolecules* **1991**, *24*, 6079
25. Lee, M.; Utsumi, K.; Minoura, Y. *J.Chem.Soc.Faraday Trans.1*, **1979**, *75(8)*, 1821
26. Otsu, T.; Tazaki, T.; Yoshioka, M. *Chemistry Express* **1990**, *5(10)*, 801
27. Melby, L.R.; Janowicz, A.H.; Ittel, S.D. *Eur. Pat. Appl. EP 196,783*
28. Burczyk, A.F., O'Driscoll, K. F., Rempel, G. L., *J. Polym. Sci., Chem.* **1984**, *22*, 3255
29. Georges, M. K., Veregin, R. P. N., Kazmaier, P. M., Hamer, G. K., *Polym. Mater., Sci. Eng.*, **1993**, *68(1)*, 6, *Macromolecules*, **1993**, *26*, 2987
30. Solomon, D.H.; Waverly, G.; Rizzardo, E.; Hill, W.; Cacioli, P., U.S.Patent, **4,581,429**, **1986**
31. Reghundhan Nair, C. P., Clouet, G., *J. Macromc!. Sci., Reviews*, **1991**, *C31*, 311
32. Mardare, D., Matyjaszewski, K. *Macromolecules* , the following article
33. Mardare, D., Matyjaszewski, K. *ACS Polym. Preprints*, **1993**, *34(2)*, 566

CAPTIONS FOR FIGURES

Fig. 1. Effect of the unimolecular transfer on polymerization degrees as a function of conversion for various ratios $b=(k_{tr}/k_p)/[I]_0$.

